YIELD AND WATER USE EFFICIENCY OF CORN IN RESPONSE TO LEPA IRRIGATION

T. A. Howell, A. Yazar, A. D. Schneider, D. A. Dusek, K. S. Copeland

ABSTRACT. *Center-pivot sprinklers are rapidly expanding on the Southern High Plains, and LEPA (low energy precision application) application methods are widely used in this region to reduce water application losses, to use the relatively low well yields, and to reduce energy requirements for pressurization. This study was conducted to evaluate LEPA irrigation response of corn (*Zea mays *L.) on slowly permeable Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll). The effects of irrigation amount were investigated in a field study during the 1992 and 1993 cropping seasons at Bushland, Texas. In 1992, a wetter than normal season, grain yields varied from 0.6 to 1.2 kg/m^2 while in 1993, which was a season with slightly less than normal rain, grain yields varied from 0.4 to over 1.5 kg/m^2 as irrigations increased from no-post plant irrigations to fully meeting the crop water use. Irrigation amounts for the full irrigation varied from only 279 mm for the wet year to over 640 mm for the more normal year. A significant relationship was found between grain yield and water use for the two years described as GY (kg/m^2) = 0.00169 [WU (mm) – 147] with an r^2 of 0.882 and a $S_{y/x}$ of 0.10 kg/m^2. Deficit irrigation of corn, even with LEPA, reduced yields by affecting both seed mass and kernels per ear. Generally, the grain yield was in proportion to dry matter yield. LEPA irrigation was shown to be efficient in terms of partitioning the applied water into crop water use. Irrigation amounts should not exceed 25 mm for alternate furrows (0.76-m rows) LEPA on the Pullman-type soils with furrow dike basins.* ***Keywords.*** *Center pivots, Corn, Cultural practices, Evapotranspiration, Irrigation, LEPA, Management, Soil water use, Sprinkler irrigation, Water.*

Irrigation is important for sustainable agriculture on the Southern High Plains, an area encompassing the high plains of Texas, New Mexico, Oklahoma, southwestern Kansas, and southeastern Colorado. Irrigation water supplies in this region are mainly from groundwater sources (Ogallala aquifer) and are being depleted, but the rate of aquifer decline has been reduced in many parts of this region by a drastic reduction in irrigated area, lower application amounts per area irrigated, and the adoption of systems with lower application losses. Musick et al. (1990) reviewed the irrigation trends on the Texas High Plains portion of this region and reported a 28% decline in irrigated area from 1974 to 1989 with a 44% corresponding decline in groundwater use during this period.

The major irrigated crops on the Texas High Plains are cotton, winter wheat, grain sorghum, and corn (Musick et al., 1990). Of these crops, corn has the greatest reported seasonal irrigation requirement (Musick et al., 1990). Major shifts from graded furrow to sprinkler, predominately center-pivot sprinklers, have reduced water applications and sustained irrigated production in this region (Musick et al., 1990; Musick and Walker, 1987).

Low energy precision application (LEPA) irrigation was developed to reduce sprinkler irrigation losses associated with droplet evaporation and drift in the high winds which commonly occur in this region, thereby saving water and energy (Lyle and Bordovsky, 1981). Originally, bubble mode LEPA applications were made to individual furrows (Lyle and Bordovsky, 1981) using furrow dikes or dams to provide temporary surface detention for the water. Later, Lyle and Bordovsky (1983) reported advantages for alternate-furrow LEPA compared to every-furrow LEPA besides the obvious reduction in hardware costs. Currently, LEPA devices are commercially available to operate in the bubble mode and chemigation mode (inverted canopy spray) (Fipps and New, 1990), as well as double-ended socks (Fangmeier et al., 1990) and newer single-ended socks. LEPA devices can operate in a flat (or slight angle) spray mode beneath the canopy, but this method wets the entire soil and part of the crop resulting in higher evaporative losses. Lyle and Bordovsky (1983) reported irrigation application efficiencies for LEPA in the bubble mode of 88% for conventional tillage and 99% for basin tillage compared to 81 and 84% for sprinkler applications, respectively, and 86 to 87% for furrow applications, respectively. Schneider and Howell (1990) reported application efficiencies based on weighing lysimeter irrigations of 96% for LEPA in the bubble mode, 82% for

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impact sprinklers, and over 100% for spray heads, which were affected more than the impact sprinkler applications by local catch from edge plants on the weighing lysimeter (inside and outside the lysimeter) caused by the close position of the spray heads to the top of the canopy. LEPA heads operating in a spray mode or in the chemigation mode should be expected to have similar application losses to conventional spray heads located just above the crop canopy, but perhaps a little less susceptible to wind effects on the spray pattern.

Howell and Phene (1983) reported static uniformities (no moving system) of 98% similar to those found by Lyle and Bordovsky (1981) and suggested that below canopy spray LEPA application losses were about 10%. Hanson and Wallender (1986) found higher dynamic application uniformities (dynamic uniformity includes the influence of machine movements) for lateral-move sprinklers near the end towers, which move at more nearly constant speeds, and lower uniformities near the center of the system, which moves more inconsistently to maintain alignment. Hills et al. (1988) reported that application efficiency, however, was not related to system speed for a lateral-move sprinkler. Hanson et al. (1988) simulated LEPA infiltration uniformity using measured tower movements and soil infiltration characteristics for various lengths of furrow dike spacings. For short dike spacings, they found infiltration uniformity was controlled by system movement uniformity, but for longer dike spacings infiltration uniformity was controlled more by soil infiltration variability. Buchleiter (1988) reported no runoff from LEPA applications on slopes of 1% or less, but for slopes greater than 3%, runoff was excessive and redistribution of LEPA applications occurred even for a system with a static uniformity (static uniformity considers only nozzle flow rates and radial distance from pivot and does not include machine movement) of 96%. Fangmeier et al. (1990) reported no effects of system movement variations on simulated application uniformity with furrow dike spacings greater than 3 m. Lyle and Bordovsky (1986) have developed continuous move electric-powered LEPA systems (both for lateral moves and center pivots, personal communication W. M. Lyle, 1992) to achieve greater movement and application uniformity with LEPA systems.

Bordovsky et al. (1992) reported that three-day irrigation frequencies were optimum for yield under deficit LEPA irrigation for cotton at Halfway, Texas. Bordovsky and Lyle (1991) reported that three-day and six-day irrigation frequencies produced better yields than 9-day and 12-day frequencies for LEPA irrigated corn, but that corn could not be deficit irrigated as effectively as cotton at Halfway, Texas, in the Southern High Plains. Spurgeon and Makens (1991) reported that LEPA irrigation frequencies between 3.5 and 10.5 days did not greatly affect corn yields at Garden City, Kansas, in the Central High Plains. They also reported that a 30% reduction in application only reduced corn yields by about 10%. Howell et al. (1991) reported that LEPA performed similarly to other more traditional methods at Bushland, Texas, for irrigating corn and sorghum, but that LEPA was more effective in partitioning the applied water into actual crop water consumption (minimizing application losses and getting applied water into the soil for crop use). Schneider and Howell (1993) found LEPA methods using the double-ended Fangmeier sock and the bubble mode produced better grain yield than either LEPA in a below canopy spray or an overhead spray mode for sorghum. The LEPA methods had higher yields, however, with greater deficit irrigation.

Center-pivot sprinkler systems are an economical, practical irrigation method for the Southern High Plains region, particularly since growing season rainfall can reliably supply part of the crop water needs thereby reducing the gross irrigation capacity. Center-pivot sprinkler irrigation (Splinter, 1976) is well suited to this environment where land resources are not the major limitation, but water resources are restricted. Variable irrigation application rates have been used with center pivots (Gilley et al., 1983; Helweg, 1988; Howell et al., 1989) to study infiltration and crop production functions for crops. Heermann et al. (1994) chronicled the U.S. advances of center pivots from under 1/4 million ha in 1966 to over 5.5 million ha of pivots and lateral moves in 1993, and they described the many advances made in irrigation application methods and management. The driving force for center pivot expansion in the Southern High Plains continues to be 1) sustained irrigated production (same or greater land area irrigated per unit water flow rate) thereby making more effective use of low yielding wells; and 2) labor savings and convenience. The main impetus seems to be a relatively stable energy price outlook and favorable interest rates to finance the capital improvement as two important factors in the economics of center pivot adoption in the Southern High Plains.

Crop yield response to irrigation and water use have been widely studied for corn. Reviews of crop yield responses to irrigation are available in Doorenbos and Kassam (1979), Stegman et al. (1980), Hanks and Rasmussen (1982), Taylor et al. (1983), Howell (1990), Howell et al. (1990) as well as several other reviews. Production functions have been widely used to describe the yield response of crops to applied water (Hexem and Heady, 1978; Vaux and Pruitt, 1983; Yaron and Bresler, 1983; and others).

The objective of this article is to report two years of research on the water use and yield response of corn to LEPA irrigation on a slowly permeable soil in the Southern High Plains environment. In addition, water use efficiency and water use partitioning from the applied irrigation water were investigated.

Methods

This study was conducted at the Conservation and Production Research Laboratory, Bushland, Texas (35°11′N Lat; 102°06′W Long; 1170 m elevation MSL) during 1992 and 1993. The soil at this site is classified as Pullman clay loam (fine, mixed, thermic Torrertic Paleustoll) (Unger and Pringle, 1981; Taylor et al., 1963) which is described as slowly permeable because of a dense B22 horizon about 0.3 to 0.5 m below the surface. This soil has a water holding capacity of approximately 250 mm of plant extractable water to the 2.0 m depth. A calcic layer at about 1.5 m significantly limits water extraction by corn below this depth (Musick and Dusek, 1980). This soil is common to over 1.2 million ha of land in this region and about one-third of the sprinkler irrigated area in the Texas

High Plains (Musick et al., 1988). The field slope is less than 0.3%.

A three-span Lockwood center-pivot sprinkler system (135 m long) was used in this study. The system was equipped with 19 mm O.D. (3/4 in.) metal drop pipes to about 2 m above the ground spaced 1.5 m apart along the system. A 1/4 turn 19-mm ball valve was placed directly beneath the steel pipe, and a Senninger Quad IV LEPA head with a 41-kPa pressure regulator was mounted on a flexible hose to about 0.3 m above the soil surface on each drop pipe. A Senninger adapter replaced the Quad IV spray plate and permitted a short length of flexible hose and a double-ended Fangmeier LEPA sock (A. E. Quest & Sons, Lubbock, Tex.) to be attached to the Quad IV LEPA head. The system operated with the normal Lockwood pivot controls at 0.033-Hz (30-s) motor controls. In 1993, a Valmont CAMS (computer assisted management system) was added for pivot control, but the same 0.033-Hz movement was maintained. Water to the system was pumped from an above-ground regulating reservoir supplied from wells in the Ogallala aquifer. Water was metered at the center pivot with a Rockwell turbine water meter. The design nozzle sizes were determined from:

$$q_i = C\,A_i \tag{1}$$

where

q_i = flow rate in L/s for the *ith* LEPA applicator

C = irrigation capacity in L s^{-1} m^{-2}

A_i = service area in m^2 of the *ith* LEPA applicator, which is given as:

$$A_i = \pi\,(2\,R_i\,r) \tag{2}$$

where

r = spacing in m served by the LEPA applicator

R_i = radius in m from the pivot point to the LEPA applicator

The nozzle diameter was selected from the Senninger handbook (nozzle diameters were available in 198-μ or 1/128-in. increments) for the 41-kPa (6-psi) pressure rating. The design value of C was selected to simulate the outer application rate for a 400 m (1/4 mile) center pivot with a C of 9.375×10^{-5} L s^{-1} m^{-2} (8.1 mm/day or 6 gpm/acre) irrigation capacity. The outer LEPA head flow rate was 0.32 L/s (5.1 gpm) to apply a 25-mm application in about 27 h for a full circle. The maximum outer tower travel speed was 0.038 m/s (7.5 ft/min). Irrigation application amounts were determined by the application rates and system travel speed, set, and measured with stopwatches. The wheel tracks were maintained on raised beds for each tower and kept dry from irrigations to avoid wheel slippage.

Commercial farm equipment was used in all farming operations. Prior to planting, nitrogen fertilizer was applied each year (table 1) and beds were formed using a disk bedder. Furrow dikes were installed following lay-by cultivation prior to LEPA irrigations in both years using a Roll-A-Cone bump-wheel diker in 1992 and a Bigham Brothers trip-roll diker in 1993. Furrow dikes were installed in each furrow in 1992 and in all but the wheel tracked furrows in 1993. The dike spacing in both years was about 3 to 4 m.

Table 1. Agronomic data for the LEPA experiments

Parameters	1992	1993
Planting date	21 April [112]*	20 April [110]
Emergence date	30 April [114]	3 May [123]
Tasseling date	11 July [193]	15 July [196]
Harvest date	6 October [280]	22 September [265]
Plant density	4.5 plants/m^2	8.4 plants/m^2
Fertilizer (preplant)		
Material rate	NH_4 13.4 g(N)/m^2	NH_4 6.7 g(N)/m^2
Date	25 March [85]	March 29 [88]
Pesticides		
Material	Atrazine	Atrazine
Date	23 April [114]	12 April [102]
Material	Accent	Accent
Date	19 May [140]	23 June [174]
Material	Lorsban	Capture/Dimethoate
Date	1 August [214]	24 July [205]
Material	Ambush/Dimethoate	
Date	18 August [230]	

* Numbers in brackets are the day of year corresponding to the date.

The experimental design was a complete randomized block with three replications, and the main treatments were irrigation levels. The treatments were named T-100, T-80, T-60, T-40, T-20, and T-0, respectively. T-100 was designed to be a full replenishment of soil water use from a 1.5-m profile. A control soil water content profile amount of 500 mm for the 1.5 m depth (0.333 m^3/m^3 mean soil water content) was maintained for T-100. The other treatments received proportional amounts to T-100 as indicated, respectively, and were all irrigated simultaneously. T-0 was a nonirrigated (post-emergence) control treatment and should not be considered as a "normal dryland" treatment because of the irrigated plant density.

The northwest quarter of the field was planted with Pioneer 3245 in 1992 and the south half was planted in 1993 with the same hybrid. Figure 1 shows a schematic diagram illustrating an example plot layout showing the 18 plots arranged radially from the pivot point. In 1992, the plots used an arc length of approximately 85° from 245° to 330°, and in 1993 the plots used an arc length of approximately 170° from 55° to 225° (all angles measured from north). The entire field had been fallowed in 1991 and both crops were started on previously fallowed soil (one year of fallow for the 1992 experiment and two years of fallow for the 1993 experiment). Plots were laid out circularly around the center pivot using six rows per plot with a row spacing of 0.76 m. Each plot had three LEPA applicators which applied water to alternate furrows, which were nonwheel traffic furrows. The LEPA nozzle size for each plot was determined by equations 1 and 2 based on the radius to the central furrow of each plot. The irrigation treatments were achieved by using a nozzle size for that particular plot location (radius from pivot) and its desired fraction of the application (C × XX, where XX is the irrigation treatment fraction like 0.2 for T-20) that would match its design flow rate. The three LEPA applicators in each plot used the same nozzle diameter despite the small difference in radius. Irrigation amount for T-100 then determined the amounts for each fraction treatment (i.e., T-60 received 60% of T-100). Irrigation amounts were determined by measuring the irrigation time and knowing the arc of the plots and the flow rate of the irrigation

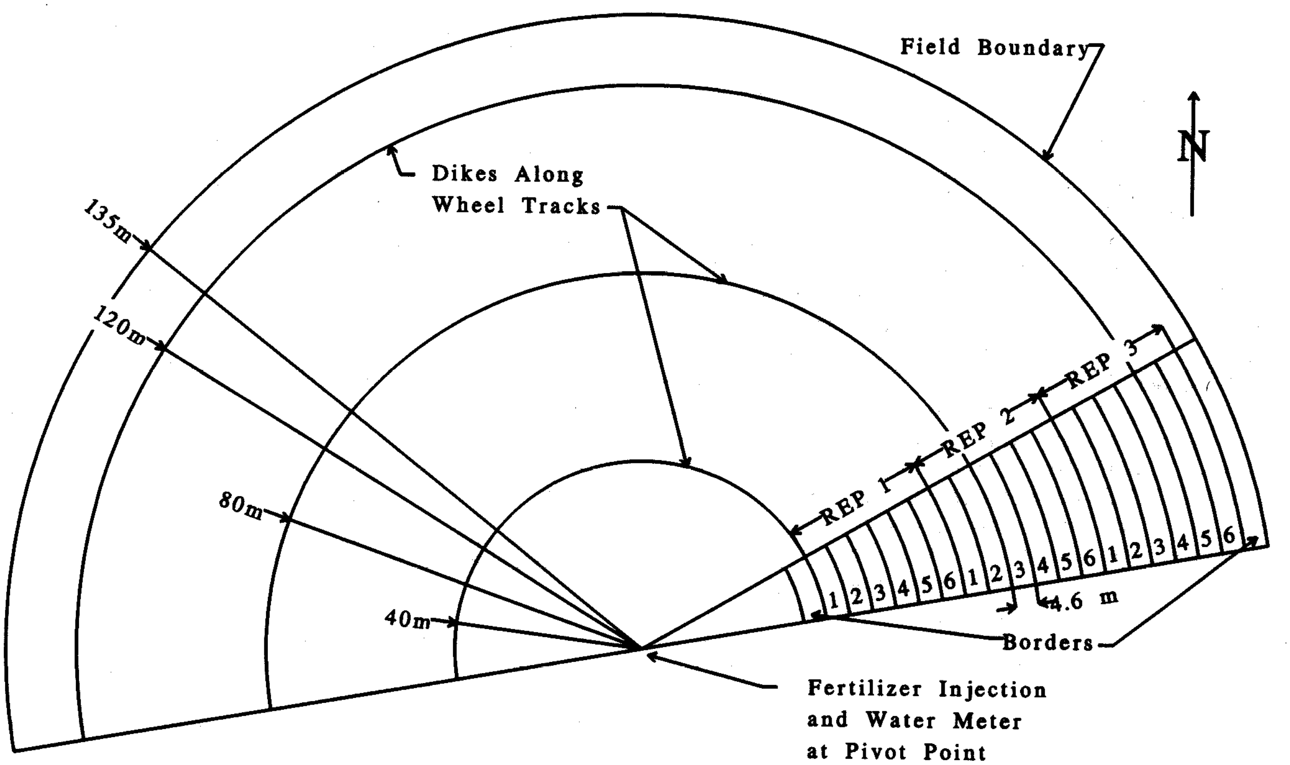

Figure 1–Example field plot layout schematic diagram.

system. Since pressure regulators were used, system flow rate was basically independent of the pressure at the pivot. Total system flow rate was monitored with a totalizing flow meter and a rate meter, which was part of the chemical injection system. Total system flow rate seldom varied by more than 2% from the design flow rates. Flow rates from randomly selected LEPA heads were periodically measured by volumetric catchment to verify system uniformity and performance. Each plot was diked on the end to minimize runoff from or runon to each plot, although water movement was permitted around the plot.

The cultural management was uniform as outlined in table 1, except post emergence fertility. Overall, fertility management for T-100 was based on pre-plant soil samples and fertilizer recommendations. Post-emergence fertilizer (Urea; 28-0-0) was applied by chemical injections into the irrigation water proportional to flow rate (Inject-O-Meter and Howard Hutchings in 1992 and 1993, respectively). The T-100 treatment was designed to receive water needs to meet the crop demand and more than adequate nitrogen so that fertility would not limit yield. The other treatments received nitrogen applications proportional to their irrigation rates. Fertility was not designed to be a limiting variable. The soil water contents in T-100 were determined weekly by soil water measurements using a neutron probe (Campbell Pacific model 503DR Hydroprobe) at 0.2 m depth increments over 2.4 m deep with 15-s counts and every three weeks in the other treatments during the seasons. The probe was field calibrated for the Pullman soil. Irrigation amounts were between 12 and 38 mm (25 mm was the typical amount to T-100), and irrigation frequency did not exceed three or four per week. Table 1 provides information on planting dates for the crops and other agronomic information.

Biomass samples of eight consecutive plants in a single row were harvested at three-week intervals in the T-100, T-60, and T-20 plots. The length of the sample (midpoint between the end plants and the next outside plant) was measured to compute the sample area. A single representative plant subsample was selected, and its leaves were separated from the stem and their area determined using an optical leaf area meter. The leaves from all the plants were removed as well. The ears (if present) were removed and counted, and then the ears, stems, leaves, and the leaf subsample were oven dried at 70° C. Biomass and leaf area index (LAI) were computed from these data. The leaf area for the whole sample was estimated as the product of the total leaf mass and the specific leaf area (m^2/kg) of the subsample.

Final grain and biomass yield were determined by hand harvesting two adjacent center rows in each plot in close proximity to the neutron tube sites. The harvest area was 4.56 m^2 in 1992 and 10 m^2 in 1993. The number of plants and ears were counted in each row, and the plants from a single row were used for a harvest index subsample and the whole yield sample was used for grain yield. The biomass and ears were dried at 70° C in an oven, and seed mass was determined for a 500-kernel subsample. Yield components of kernel numbers and kernels per ear were computed based on the grain yield, mean kernel mass, and numbers of ears. The ears were shelled by hand.

Water use was estimated based on a one-dimensional soil water balance using the neutron soil water measurements and assuming that runoff and deep percolation were negligible. Water use was the total of seasonal soil water depletion (emergence to harvest) plus rainfall and irrigations during the same time period. Water use efficiency was computed as the ratio of grain (dry basis) to water use. Irrigation water use efficiency was determined as the ratio of crop yield for a particular treatment less the T-0 yield to the applied irrigation water for that treatment.

Results and Discussion

The 1992 growing season had higher than normal rainfall of 431 mm during the season (table 2 and fig. 2), and the 1993 season was more typical of normal rainfall patterns with only 241 mm of rainfall during the season. Both seasons had single-day rainfall amounts exceeding 50 mm. Air temperatures in 1992 were somewhat cooler than normal, and 1993 had more normal air temperatures (table 2, figs. 2 and 3). The reference ET values computed for 0.5-m-tall alfalfa using the Kimberly-Penman equation (REF-ET, V2.14; Allen, 1990) are shown in figure 4, and 1993 had about 70 mm more reference ET compared to 1992 for the April-October months. Reference ET was noticeably lower at DOYs 140-160 (late May) in 1992. These growing season environments are typical of the diversity to be expected in the Southern High Plains. Figures 2 and 3 depict some of the daily climatic conditions during the study. Table 2 summarizes the monthly climate data compared with long-term climate data for Bushland.

The high rainfall during May and June in 1992 interfered with plans to fertigate the crop, and only two applications of 3.0 g(N)/m^2 were made on 15 July (197) and 21 July (203) just after tasseling. In 1993, T-100 received 21 g(N)/m^2 from late May until 26 July (207) just after silking. The other treatments received proportionately less fertigation. The total nitrogen application to T-100 was 19.4 g(N)/m^2 in 1992 and 28 g(N)/m^2 in 1993; both very similar to the recommended amounts for those years based on the soil samples and the yield goal of 1.6 kg/m^2 (250 bu/acre). Eck (1984) reported fertilizer nitrogen requirements between 14 and 30 g(N)/m^2 to maximize the response of corn to nutritional status on the Pullman soil with surface irrigation methods and adequate irrigation. Lamm and Manges (1991) reported the nitrogen requirement of drip irrigated corn at Colby, Kansas, of 28 to 31 g(N)/m^2 with a yield plateau level at 26 g(N)/m^2. Although fertility level was not held constant across the treatments, it was managed in a consistent manner to avoid any nutrient deficiencies in the crop. It is unlikely that crop yields were affected to any significant extent from the differing nitrogen applications, which were intended to be more than adequate for the water availability of the particular treatment.

Germination and emergence irrigations were applied in the spray mode uniformly in both years. In 1992, 25 mm was applied on 23 April (114), and another uniform irrigation of 25 mm was applied on 11 May (132) using the

Table 2. Climatic data summary for the experimental years contrasted to historical data for Bushland, Tex.

Month	Max. Temp. (° C)	Min. Temp. (° C)	Dew Point Temp. (° C)	Solar Rad. (MJ/m^2)	2-m Wind (m/s)	Rain (mm)	ET$_r$ PMon* (mm/d)	ET$_r$ KPen† (mm/d)
1992								
April	22.0	6.0	2.9	21.9	3.9	15	7.5	6.0
May	23.5	9.8	6.0	20.7	4.0	81	7.8	6.9
June	28.1	13.9	10.4	24.9	3.7	165	8.9	8.5
July	31.5	17.1	12.8	25.8	4.5	68	11.0	10.5
August	28.7	15.6	12.2	21.4	4.3	102	9.0	8.5
September	28.0	12.5	7.8	20.0	4.7	9	9.8	8.5
October	23.6	6.1	1.5	15.2	4.0	6	7.7	6.0
1993								
April	21.0	3.4	−1.4	21.9	5.2	15	8.8	7.0
May	25.0	9.9	5.2	23.5	5.1	16	9.6	8.4
June	30.2	15.4	9.8	24.3	5.5	57	12.0	11.0
July	32.4	18.9	13.9	24.7	4.8	96	11.7	10.9
August	30.0	16.5	13.4	21.2	3.5	43	8.5	7.9
September	27.7	11.0	9.0	19.6	3.7	15	8.1	7.0
October	20.3	4.2	2.6	14.8	4.1	22	6.0	4.9
	55-Year Means			21-Year Mean		55-Year Mean		
Mean Climatic Data								
April	21.8	4.2		22.5		26		
May	26.0	9.6		24.4		68		
June	30.7	14.8		26.3		78		
July	32.5	17.2		25.6		65		
August	31.6	16.4		22.8		71		
September	27.9	12.2		19.2		49		
October	22.7	5.9		15.4		40		

* Alfalfa reference ET Penman-Monteith equation (Allen, 1990).
† Alfalfa reference ET Kimberly-Penman equation (Allen, 1990).

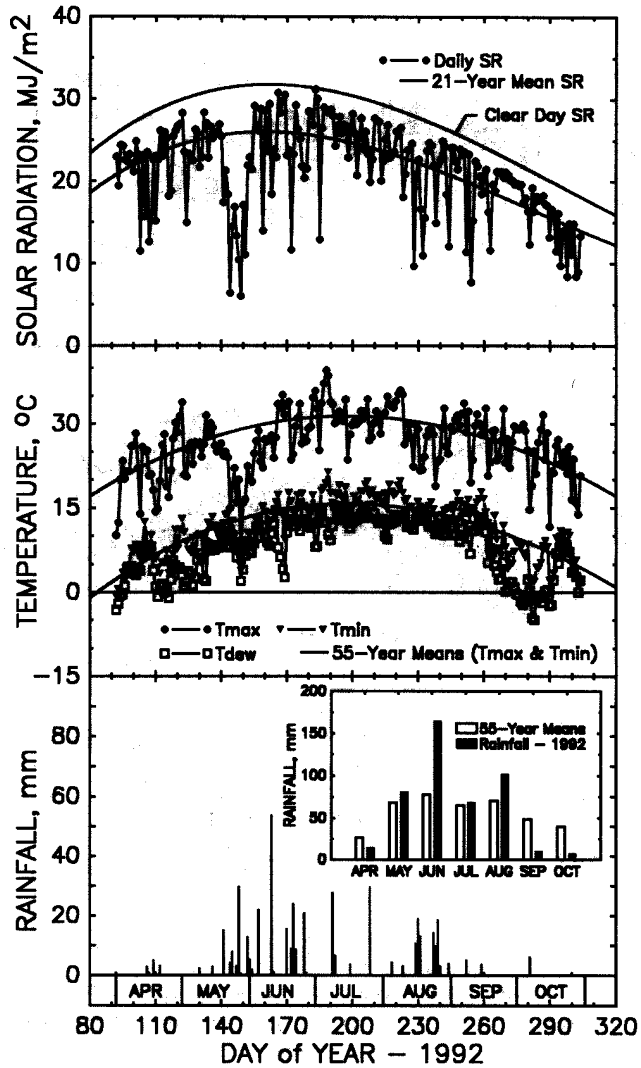

Figure 2–Climatic data summary for 1992 at Bushland, Tex.

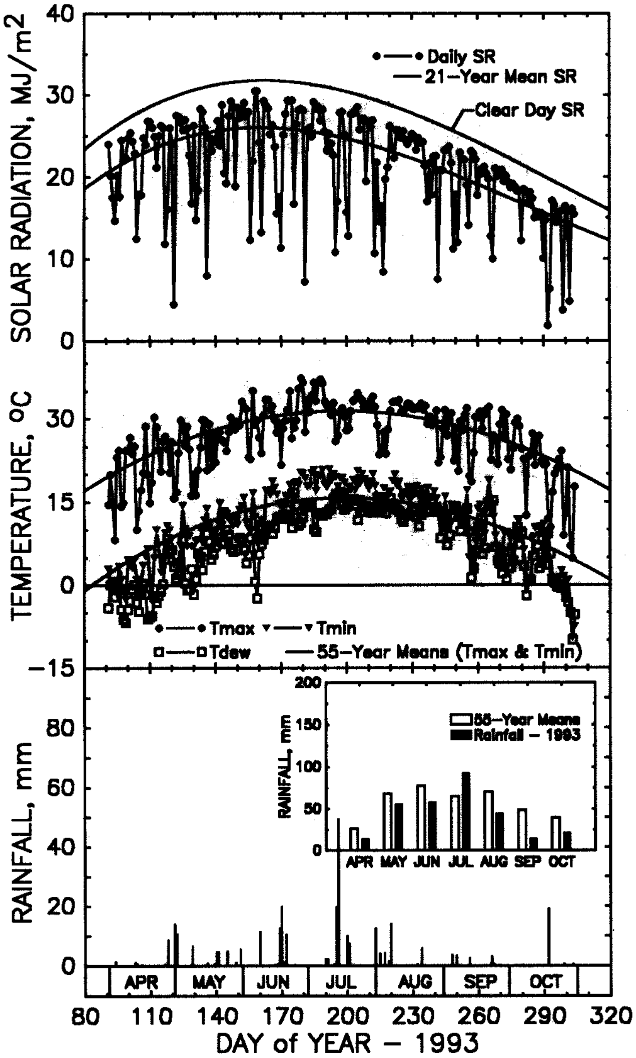

Figure 3–Climatic data summary for 1993 at Bushland, Tex.

LEPA bubble mode. In 1993, three germination and emergence irrigations were uniformly applied on 20 to 21 April (25 and 38 mm, respectively) and on 27 April (15 mm), all in the spray mode.

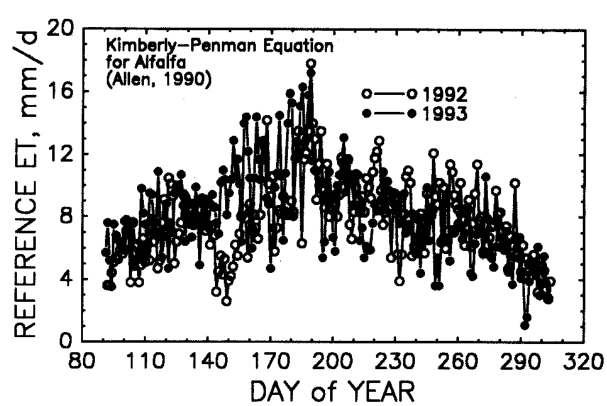

Figure 4–Reference ET for 1992 and 1993 seasons at Bushland, Tex., computed with the Kimberly-Penman equation for 0.5-m-tall alfalfa (Allen, 1990).

Alternate furrow LEPA irrigations of 25 mm filled the furrow dike storage volume. Occasionally a dike overtopped, but usually the bed overtopped, spilling water into the adjacent diked furrow (normally dry) before a dike failed. The dikes were effective in holding the 50 mm of single event rains (note with alternate furrows that the rainfall storage volume is twice the LEPA storage volume) that occurred in each year with minimal field runoff (some redistribution likely occurred around the circular plots). In 1993, a large rain occurred the evening after an irrigation of 25 mm that day without any noticeable plot runoff. Clearly, LEPA without surface storage capacity would not be expected to function as envisioned even for this relatively flat topography. Actually, LEPA applications of 20 mm (the amount applied to T-80 for a 25 mm T-100 application) appeared to be about optimum for filling the furrow dike basins and preserving the dikes on Pullman clay loam. Applications with the double-ended Fangmeier LEPA sock performed superior to LEPA bubble and LEPA spray modes that we used in previous years (Howell et al., 1991) by avoiding erosion and siltation of the furrows and erosion of the furrow dikes by the irrigation water. LEPA should be managed to apply as much water as can be efficiently stored in the furrow-dike basins, and then irrigation frequency is simply determined by the gross irrigation capacity. For most systems in this region, maximum LEPA applications with alternate furrow systems should not exceed 25 mm for 0.76-m rows for corn, and the resulting frequency would be 3.1 to 3.8 days depending on the gross irrigation capacity [8 mm/day (6 gpm/acre) to 6.5 mm/day (5 gpm/acre)].

The maximum LAI occurred at tasseling both years with 1993 having a slightly greater maximum LAI (figs. 5 and 6). Leaf area index declined more rapidly following anthesis in 1992 than in 1993. Maximum above-ground

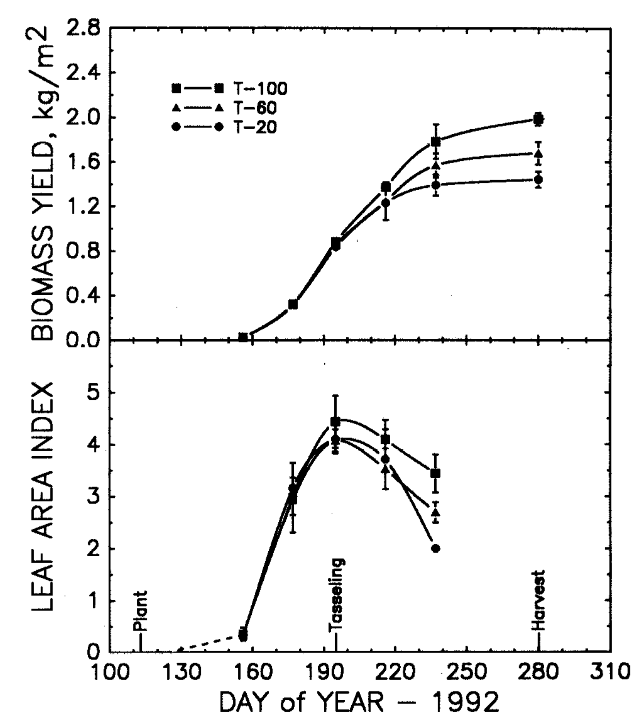

Figure 5–Above-ground biomass and LAI for T-100, T-60, and T-20 treatments in 1992.

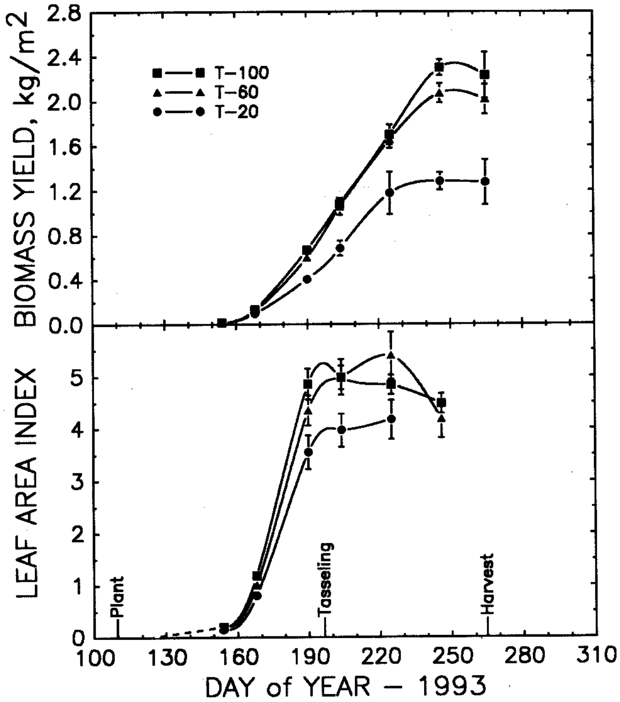

Figure 6–Above-ground biomass and LAI for T-100, T-60, and T-20 treatments in 1993.

Table 3. Yield and yield component data

Treatment	Grain Yield* (kg/m²)	Harvest Index† (kg/kg)	Biomass Yield† (kg/m²)	Kernels Mass (mg/kernel)	Kernels Numbers (no./m²)	Kernels per Ear (no./ear)
1992						
T-100	1.246a‡	0.574	1.986a	308	4386a	716a
T-80	1.236a	0.568	1.879a	318	4587a	703a
T-60	1.041b	0.551	1.680b	310	4054ab	663ab
T-40	0.972bc	0.538	1.548bc	330	3693bc	522bc
T-20	0.826c	0.532	1.441c	318	3135c	474c
T-0	0.603d	0.505	0.934d	301	2449d	422c
$LSD_{0.05}$	0.061	ns	0.073	ns	258	60
1993						
T-100	1.550a	0.572a	2.232a	315a	4165a	512b
T-80	1.482a	0.573a	2.228a	325a	3857a	491b
T-60	1.285b	0.578a	2.017a	291b	3740ab	478b
T-40	1.086c	0.511ab	1.671b	268c	3429b	592a
T-20	0.774d	0.459b	1.273c	220d	2986c	461b
T-0	0.400e	0.337c	0.830d	193e	1756d	296c
$LSD_{0.05}$	0.084	0.077	0.278	23	427	61

* Grain yield adjusted to 15.5% w.b. (wet basis).
† Harvest index and biomass samples were different areas than the grain yield samples.
‡ Numbers followed by different letters are statistically different (P < 0.05 level) based on the least significant difference (LSD).

biomass was about 2.0 kg/m² in 1992, while it was slightly over 2.3 kg/m² in 1993. Both of these years had LAIs and biomass values for the T-100 treatment typical for high yielding corn. The T-20 and T-60 treatments reduced biomass in both years, but to a much greater extent in the drier 1993 season. LAI was not greatly affected by the treatments in 1992 (for T-20 and T-60), but T-20 reduced LAI to a significant extent in 1993. T-60 biomass was not different from T-100 until after anthesis in both years, and T-60 achieved equivalent LAIs to T-100 in both years. Maximum dry matter growth rates of 25 to 28 g m^{-2} d^{-1} were maintained from before tasseling until mid-grain fill by T-100. T-60 maintained similar dry matter growth rates only until tasseling in 1992, but its growth rates maintained these peak values beyond tasseling in 1993. T-20 had reduced dry matter growth rates much earlier in the 1993 season, but maintained its growth rate near T-100 until tasseling in 1992 when more early season rainfall occurred.

Grain yield and yield components data are summarized in table 3. Grain yields ranged from 0.4 to over 1.5 kg/m² in 1993, but ranged only from 0.6 to 1.2 kg/m² in the wetter 1992 year. Yields were limited in 1992 by the growing conditions and possibly the lower plant density of only 4.5 plants/m² (table 1) although it was seeded at about 7 plants/m² in that year. Harvest index (ratio of grain yield to biomass yield) was not reduced by the irrigation level in 1992, but was more affected in 1993 by the more severe soil water deficits that developed. Likewise, kernel mass was not affected in 1992 when yield effects were almost entirely related to reduced numbers of kernels per ear. In 1993, grain yield was equally affected by both reduced kernel mass and kernels per ear. The large difference in kernels per ear between the two years was due to the much lower plant density in 1992 compared with 1993 (table 1). Basically, about 4,000 to 4,100 kernels/m² are necessary to maximize grain yield for this hybrid. Grain yields were affected similarly to dry matter production.

The soil water contents were slightly wetter in 1993 at emergence (fig. 7) compared with 1992. Water uptake by corn occurred mainly in the 0- to 1.5-m layer as found by Musick and Dusek (1980). However, in 1993 corn extracted more water from below the 1.5 m depth, perhaps due to the differing onsets of soil water deficits before anthesis. The increased soil water variability below the 1.5 m depth shown in figure 7 is indicative of the variability in depth to calichie and crop rooting into the calichie layer, particularly for the higher deficit treatments —T-60 and T-20. Table 4 and figure 7 indicate similar soil water extractions for T-100 and T-60 (9 mm more for T-60 in 1992 and 7 mm more in 1993), but T-20 had slightly greater extraction than either in 1993 (25 mm more than T-100 and 18 mm more than T-60). Table 4 shows the seasonal soil water depletion information for all the treatments. In 1993, soil water extraction extended below the 1.5 m depths, particularly for the T-40, T-20, and T-0 treatments (fig. 7). Although drainage (either steady- or nonsteady-state) could be occurring, the temporal distributions of these deeper soil water content changes clearly indicate that they were the result of root uptake and not drainage. Even corn can root into the caliche layer of the Pullman soil profile and extract small amounts of water which was thought mainly possible only by wheat, sugarbeet, and sunflower (Ratliff et al., 1983).

Table 4 provides a summary of the water use and water use efficiency data. Water use varied only from 533 to 786 mm in 1992, but varied from 383 to 973 mm in the more normal year of 1993. Table 5 provides a summary of previous Bushland corn irrigation studies for comparison with this experiment. Water use has been reported to vary from 670 to 790 mm by Musick and Dusek (1980), from 783 to 937 mm by Eck (1984), 838 mm by Howell et al. (1989), and from 699 to 785 mm by Steiner et al. (1991),

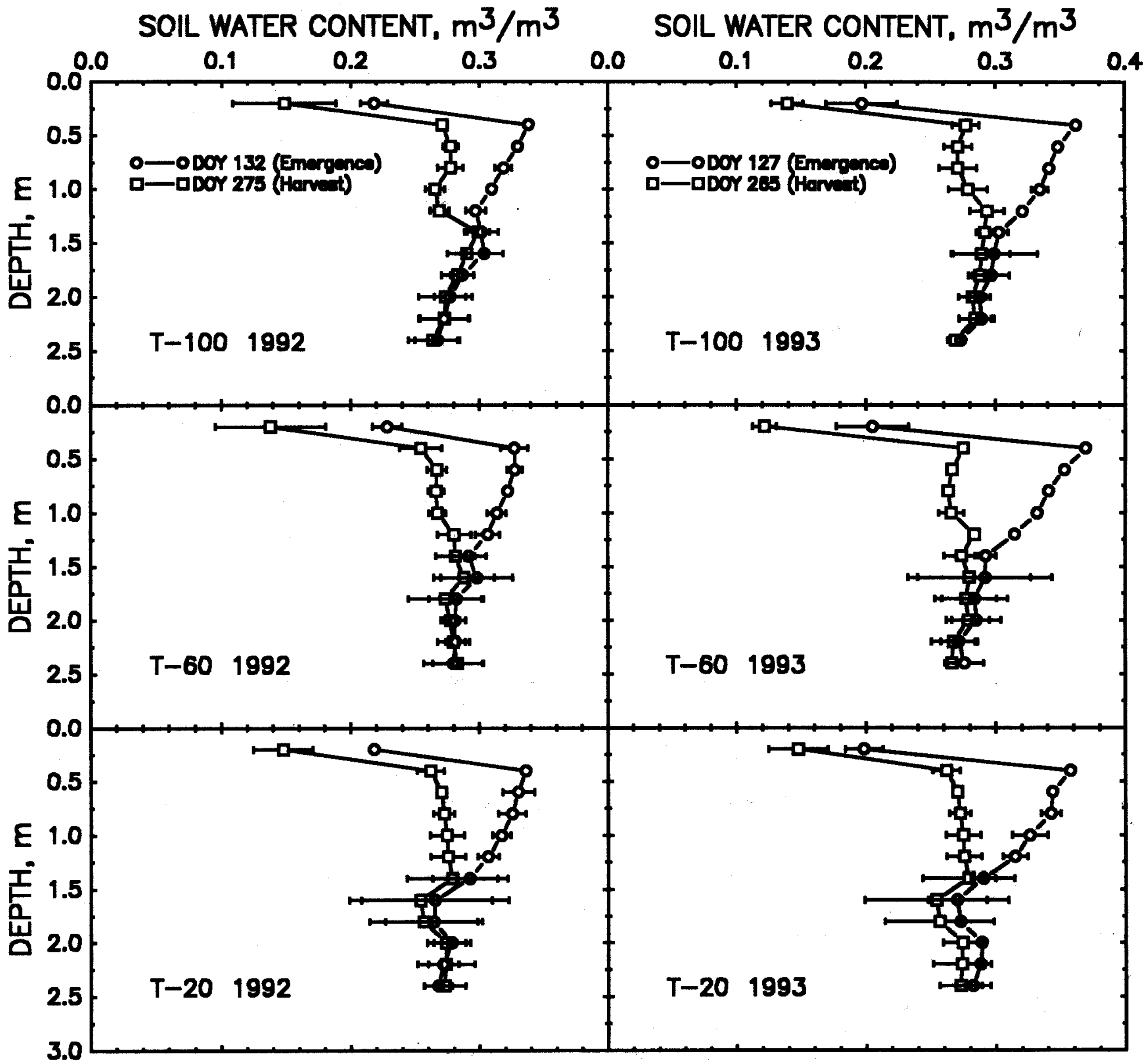

Figure 7–Soil water contents measured at emergence and harvest in 1992 and 1993 for T-100, T-60, and T-20 treatments.

which was measured using weighing lysimeters for adequately irrigated corn at Bushland. The 187-mm difference in water use for the T-100 treatment in 1992 and 1993 is partially explained by the higher evaporative conditions in 1993 (fig. 4) and partly by the earlier leaf area development in response to the warmer environment (table 2 and figs. 2 and 3). These water use amounts are within those reported from previous Bushland corn irrigation experiments for graded furrow, level border, and sprinkler methods and do not clearly show a large irrigation savings attributed to the LEPA method itself (table 5).

Water use efficiency values (table 4) varied from 0.89 to over 1.5 kg/m^3 which are similar to reported values from 1.05 to 1.23 kg/m^3 by Musick and Dusek (1980), up to 1.42 kg/m^2 by Eck (1984), and 1.18 kg/m^3 by Howell et al. (1989) (note the grain water content was corrected to dry grain), but clearly indicative of the efficient use of water possible with LEPA. Table 5 provides a summary for comparison of water use efficiency from this experiment to previous Bushland studies of corn response to irrigation. LEPA produced a good water use efficiency which was higher than the previous studies at Bushland using surface methods. The water use efficiency for LEPA from this experiment was slightly more than the previous sprinkler study by Howell et al. (1989), but slightly less than that computed using data from Steiner et al. (1991) based on lysimeter determined water use.

The irrigation water use efficiency was computed as:

$$IWUE_t = (GY_t - GY_{ni})/IRR_t \qquad (3)$$

where

$IWUE_t$ = of treatment t (kg/m^3)
GY_t = grain yield (dry) of treatment t (g/m^2)
GY_{ni} = grain yield of a nonirrigated treatment (g/m^2)
IRR_t = applied irrigation water to treatment t (mm)

Table 4. Water use and water use efficiency data

Treatment	Seasonal Irrigation (mm)	Soil Water Depletion* (mm)	Water Use† (mm)	Water Use Efficiency‡ (kg/m^3)	Irrigation Water Use Efficiency§ (kg/m^3)
1992					
T-100	279	70	786a‖	1.34ab	1.95
T-80	228	72	737b	1.42a	2.35
T-60	178	79	695c	1.27ab	2.08
T-40	127	104	668d	1.21b	2.46
T-20	76	74	588e	1.19b	2.48
T-0	25	71	533f	0.97c	—
$LSD_{0.05}$		ns	13	0.09	
1993					
T-100	644	88c	973a	1.35c	1.51
T-80	515	92bc	848b	1.48ab	1.78
T-60	386	95bc	731c	1.48ab	1.94
T-40	258	104bc	593d	1.55a	2.25
T-20	129	113b	483d	1.36bc	1.71
T-0	0	142a	383e	0.89d	—
$LSD_{0.05}$		23	23	0.13	

* Difference from initial soil water contents for a 2.5-m profile and ending soil water contents measured by neutron attenuation.
† Total of soil water depletion, seasonal irrigations, and rainfall during the period of neutron measurements.
‡ Ratio of grain yield (dry basis) to water use.
§ Ratio of treatment grain yield (dry basis) minus T-0 yield to seasonal irrigation.
‖ Numbers followed by different letters are statistically different ($P < 0.05$ level) based on the least significant difference (LSD).

GY_{ni} was taken as the yield from T-0. Except for T-20 in 1992, IWUE decreased from about 2.2 to 2.5 kg/m^3 at the highly deficit irrigation levels to about 1.5 to 1.9 kg/m^3 at the highest irrigation levels.

The relationship between grain yield and crop water use is shown in figure 8. The intercept represents soil water evaporation (and possibly some crop transpiration necessary to establish some grain yield), and the slope is perhaps a better indication of the water use efficiency of corn of 1.69 kg/m^3. This slope can be compared with those varying from 1.46 to 2.06 kg/m^3 reported by Musick and Dusek (1990) and 2.87 kg/m^3 reported by Howell et al.

Table 5. Comparison of water use and water use efficiency of fully irrigated corn from this study using LEPA and other studies at Bushland, Tex.

Study	Year	Irrigation Method	Water Use (mm)	Water Use Efficiency* (kg/m^3)
Current Study	1992	LEPA	786	1.34
	1993		973	1.35
Musick & Dusek (1980)	1975	Surface	775	1.18
	1976		667	1.24
	1977		680	0.85
Eck (1984)	1976	Surface	937	0.81
	1977		984	0.72
	1978		970	0.83
	1979		783	1.42
Howell (1989)	1987	Sprinkler	838	1.18
Steiner et al. (1991)	1989	Sprinkler	699	1.50
	1989		683	1.47
	1990		731	1.33
	1990		785	1.43

* Grain yields based on 0% w.b.

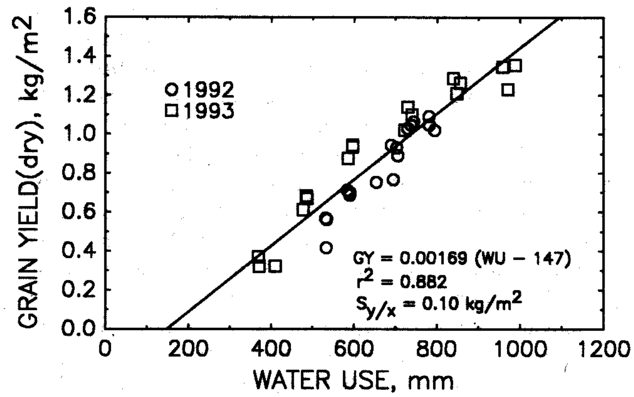

Figure 8–Relationship between grain yield and water use for LEPA irrigated corn at Bushland, Tex., in 1992 and 1993.

(1989) at Bushland to 1.23 kg/m^3 reported by Wenda and Hanks (1981), 1.95 kg/m^3 reported by Stewart et al. (1975), 0.822 kg/m^3 determined for data presented in Hillel and Guron (1973), 2.36 kg/m^3 reported by Stegman (1982), 1.1 to 3.4 kg/m^3 reported by Hanks et al. (1978), and a range of other studies that could be cited (note in most cases the grain water content was corrected to 0% wc). Tanner and Sinclair (1983) proposed that this slope was inversely proportional to the mean atmospheric vapor pressure deficit (VPD), mainly daytime VPD. It may be impossible to prove that LEPA irrigation produced a different slope from other irrigation methods. Suffice to summarize, the slope of the grain yield and water use relationship for corn at Bushland irrigated by LEPA is similar to those reported for other locations and for other irrigation methods. Although some differences are apparent for the 1992 and 1993 data shown in figure 8, the composite data are well represented by the single regression line. A quadratic fit was not significant. It does appear, as seen in figure 8, that grain yield tended to level at a water use amount of about 850 mm. Attempts to fit the data with piece-wise linear segments to illustrate this leveling were not successful.

The distinct relationships between grain yield and irrigation can be seen in figure 9. In 1992, the relationship was mainly linear (a quadratic regression was not significant), but in 1993 it was more quadratic. The differences between the two years is due to the differing

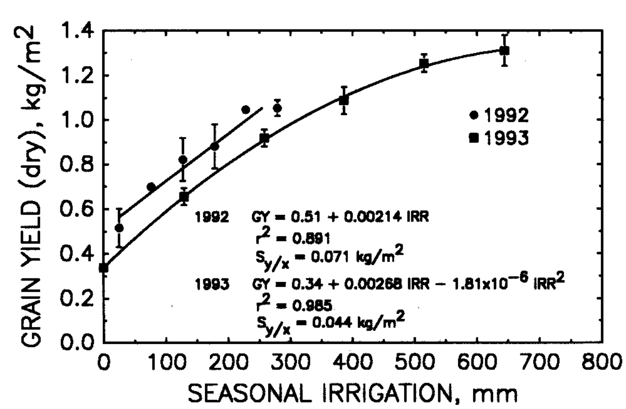

Figure 9–Relationships between grain yield and seasonal irrigations for LEPA irrigated corn at Bushland, Tex., in 1992 and 1993.

seasonal rainfall amounts and distribution. The reason for these relationships is more clearly seen when analyzed as water use partitioned from the applied irrigation water following the method of Martin et al. (1984) and earlier described by Stewart and Hagan (1973). Figure 10 shows that in both years a high proportion of the applied water was consumed in water use (admittedly some unknown amounts of runoff and drainage through the rootzone could be included in the water use values). In 1992, over 90% of the applied water was contributed to crop water use and very little remained in the soil (not used by the crop) with the management levels used in these studies. Perhaps a better use was made of the rainfall in 1992 than in 1993, since the partitioning fell slightly in the second year. LEPA, if managed properly, can be extremely efficient in permitting a maximum amount of the applied water to be used by the crop and avoiding wastes to deep percolation, storm runoff, and application losses (Martin et al., 1984; Howell et al., 1990) because smaller applications can be used avoiding having a full soil water profile and by having only alternate furrow irrigation application providing greater rainfall retention. The alternate furrow application pattern provides reduced surface evaporation losses since less than one-half of the soil is actually wetted and permits deeper infiltration into the rootzone since the application is concentrated into a single furrow (or basin).

CONCLUSIONS

LEPA irrigation of corn on Pullman clay loam was found to be comparable to other irrigation methods. LEPA applications on typical furrow-dike basins should not exceed 25 mm on Pullman soil to avoid overfilling the basins. The double-ended Fangmeier LEPA socks prevented deterioration of the furrow dikes during the irrigation season from erosion of the dike by the LEPA applications. The furrow-dike basins could store up to 50 mm of rain (or 25 mm of LEPA applications applied to alternate furrows).

Deficit LEPA irrigation of corn at Bushland generally reduced grain yield by reducing both seed mass and kernels per ear. The grain yield in most cases was closely related to the dry matter yield, and generally the harvest index was relatively consistent across a wide range of water levels, but did decline as the irrigation deficit increased. Deficit-irrigated corn was shown to be able to extract soil water (to a limited extent) from the caliche layer occurring at about 1.5 in the Pullman soil. Only rather severe deficit LEPA irrigation treatments reduced LAI, but even small deficits tended to reduce biomass. Maximum dry matter production rates of 25 g m^{-2} d^{-1} were maintained at tasseling with the more fully irrigated treatments.

Irrigation demand depends strongly on the distribution and amount of growing season rainfall. In 1992, with a larger than normal rainfall amount of 431 mm, only 279 mm of irrigation was required for the T-100 treatment compared with 644 mm of irrigation required by T-100 in 1993, a year with only 241 mm of rainfall. Water use for the full irrigation level (T-100) varied from 786 mm in 1992 to 973 mm in 1993 at this site for LEPA-irrigated corn and was not greatly different from full irrigation water requirements of corn using other irrigation methods in this location.

The relationship between corn grain yield and water use and water use efficiency for LEPA irrigation was shown to be similar to other irrigation methods at Bushland and at other locations. The LEPA irrigation method permitted precise control of the irrigation application and provided uniform irrigations. LEPA can avoid some application losses. With proper management, LEPA should nearly maximize partitioning of the applied water to meet the crop water use needs. However, LEPA requires surface storage or high-intake soils to avoid surface redistributions from the applied water and to avoid field runoff from both rainfall and irrigation.

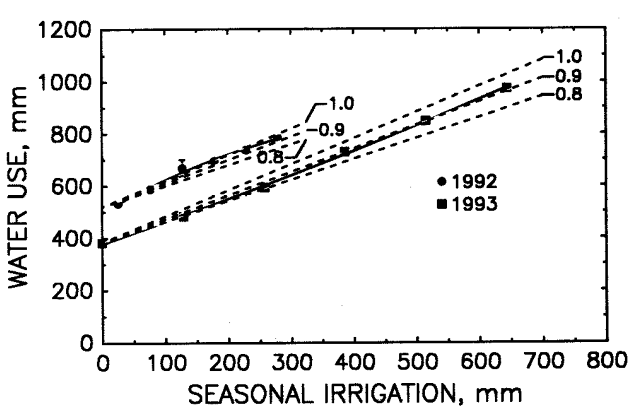

Figure 10–Relationships between water use of corn and seasonal irrigations applied with LEPA in 1992 and 1993 at Bushland, Tex. The dashed lines represent constant partitioning fractions of 100, 90, and 80% of the applied water.

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